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Non-uniform illumination in concentrating solar cells

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ABSTRACT

After a gap of more than two decades, Concentrator Photovoltaics (CPV) technology is once again under spotlight for making use of the best available solar cell technologies and improving the overall performance. CPV finds its use in a number of applications ranging from building integration to huge power generation units. Although the principles of solar concentration are well understood, many practical design, operation, control issues require further understanding and research. A particular issue for CPV technology is the non-uniformity of the incident flux which tends to cause hot spots, current mismatch and reduce the overall efficiency of the system. Understanding of this effect requires further research, and shall help to employ the most successful means of using solar concentrators. This study reviews the causes and effects of the non-uniformity in the CPV systems. It highlights the importance of this issue in solar cell design and reviews the methods for the solar cell characterization under non-uniform flux conditions. Finally, it puts forward a few methods of improving the CPV performance by reducing the non-uniformity effect on the concentrator solar cells.

Contents

1. Introduction

Concentrating photovoltaics (CPV) seems to be the much needed breakthrough enabling the solar energy industry to be

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competitive in the power generation [1,2] market. Although, discovered more than three decades ago, this technology did not gain the needed momentum due to several reasons [3]. Today, with increasing solar cells efficiencies and their associated high costs for manufacture, CPV technology is back into business to make the best use of the technology advancement and the solar cell materials. CPV technology promises not only to reduce the cost of the overall system, but also increases the amount of power produced. It reduces the intake of raw materials needed for manufacture, improves recycling and makes it economically feasible to be used for a number of applications. A recent paper highlights the benefits of using CPV [4] and its role in increasing overall system efficiency and reducing the use of semiconductor material. A typical CPV system consists of several elements essentially including an optical system which could be either reflective or refractive, Concentrator solar cells, a thermal dissipation system, a casing or support system and a tracking mechanism. The overall performance of the CPV system depends on how effectively each of these elements performs individually and collectively. Using the basic principle of focusing large amount of sunlight on a small solar cell by the help of an optical concentrator, which could be a Fresnel lens [5–7], parabolic troughs [8], dishes [9,10] or v-groove mirrors [11–13], refractive prism [14–17], luminescent glass [18–20], compound parabolic concentrator [21–26] or some other optical system [27,28], solar concentration is sought to be one of the most effective ways of reducing overall energy generation costs. The principles of optical concentration are well established [29–33] and explained for applications in both photovoltaics and solar thermal applications. The research and development of CPV technology effectively started at the National Sandia Laboratories in 1976 with Sandia-I and Sandia-II spurred by the oil crisis in 1973 [34]. A brief history on the concentrators is presented by highlighting the factors needed to push forward the large scale production of concentrators [35]. One of the most early and successful implementation of concentrator PV saw its dawn in Saudi Arabia [36], where a complete village was powered using Concentrating PV system comprising of 160 arrays with 4000 m^2 area and generating a power of 350 kW peak output. However with the end of oil crisis and absence of any significant breakthroughs the research and development in this area slowed down in the next few decades. In later times, the interest shifted towards applications for building integration; the CPV systems once again came back to picture with the development of several CPV systems for building applications like sky lighting, façade applications, wall curtains and few other applications still undergoing development. A recent review demonstrates latest developments and the scale of this industry [37]. With PV industry gaining impetus in power production recently a number of new companies are now coming forward to introduce CPV systems which can effectively produce electricity and readily compete with the conventional electricity costs [38].

The use of CPV systems in BIPV and power generation remains to be the most important. Recently a hybrid power and desalination plant able to produce 30,000 m^3 of pure water per day working on HCPV technology with a concentration ratio of 1500x was announced in the kingdom of Saudi Arabia [39]. Several other power plants working on CPV technology are also being announced [40]. With these figures growing higher and higher CPV technology seems very promising. Concentrating the sunlight by using concentrators reduces the area of expensive solar cells or modules, and, increases their efficiency. However, this technology has one shortcoming as it requires continuous tracking to keep it normal to the sun.

The amount of concentration produced by using a concentrator varies over a wide range of values. A geometrical parameter "Concentration Ratio" defined as the ratio of the areas of the concentrator and the solar cell is used for distinguishing the type of concentrator. Based on the illumination intensity it focuses on the solar cell, the concentrators may be classified as Low Concentration Photovoltaics (LCPV), Medium Concentration Photovoltaics (MCPV) and High Concentration Photovoltaics (HCPV) systems further details of which can be found under [41]. These systems utilize different type of solar cell technologies depending on the area of application and the economics of the system.

1.1. Concentrating solar cells

The Solar Cell is the key element of any CPV system, and its design plays an important role in enhancing the performance of the entire CPV system. In CPV systems special kinds of cells are required which can operate at high concentrations and elevated temperatures.

These concentrator cells differ significantly from one-sun cells in several ways, including the method of manufacture and the overall cell design and their performance, the concentrator solar cells generally include bus bars around the perimeter of the cell which can be accommodated without blocking any of the incoming light [42]. In addition to the bus bars, they have fingers which carry the current generated in the emitter towards the busbars. Depending on the concentration ratio, application and the type of concentrator different types of solar cells are utilized for having an optimum performance and reliability of the system. The type of solar cells to be used in the CPV system can be single junction silicon cells [1, 21, 23, 43–46], thin films [47] or multi-junction cells [4, 44, 48–50]. For applications demanding high concentrations like point focused systems, multi-junction solar cells are needed which can perform under high concentration and extreme temperatures and are durable for a large period of time. This demands not only special materials and chemical processing but also a very effective design [51] which further increases the cost of the solar cells in the CPV systems. These types of systems are mainly used in power generation where the high investment gets paid off [52]. For applications that are line focused there is a scope of utilizing cheaper materials or the usual Si solar cells with design improvements, and improved efficiencies. The LCPV and MCPV systems use some high quality single junction silicon solar cells, which are cost effective as their manufacturing is not much different from those used in conventional PV panels. These Si solar cells can be manufactured by making improvements in material quality having longer minority carrier lifetimes [46], proper grid design, light trapping and improved surface passivation. These solar cells usually have a single junction and are capable of absorbing limited regions of the solar spectrum. On the contrary multi-junction solar cells (III–V Cells) [4] utilize a broad portion of the visible spectrum but are expensive. Multi-junction solar cells are made of several layers of semiconductor material so that different layers of the cell can absorb different regions of the light spectrum making them capable to utilize more of the spectrum and reach higher efficiencies. Few MCPV and almost all HCPV systems use multi-junction solar cells [53]. The cells utilize materials having different band gaps and are bonded together to utilize maximum portion of the visible spectrum which tremendously increases its efficiency. Although, it has not been very long since these technologies came into existence and reliability studies have been carried out [54] under simulated conditions, these results show that these cells are expected to perform for at least 30 years.

In order to obtain high efficiency low cost cells, Laser Grooved Buried Contact (LGBC) [55] solar cell technology could be used to obtain efficiencies higher than 18% on mono-crystalline CZ wafer at lower cost. This process utilizes a laser to scribe grooves into

the front surface which are subsequently plated electrochemically to form the front contact pattern. These cells are suitable for low to medium concentration systems due to selective emitter structure and low contact shading. Recent developments in order to improve the process have been highlighted by Serenelli et al. [56]. Smaller cells could be used instead of the large ones in order to produce the same amount of power as can be seen in Fig. 1. Smaller cells ensure reduced material cost, effective heat transfer in the system, smaller currents and can be used in applications involving building integration.

For high concentration applications multijunction or tandem cells are utilized. These cells are either made by stacking solar cells with different band gaps mechanically or different materials are all grown on a single substrate and connected in series using tunnel diodes. Depending on the stacking arrangement of p–n junctions with different bandgaps energies, these cells have the capability to utilize major portion of the solar spectrum very conveniently and reach higher efficiencies which is currently more than 40%.

The triple junction solar cells function similarly to the conventional series connected single junction solar cells except that in the triple junction cell the subcells are connected in series by tunneling diodes resulting in a cell voltage which is the sum of the individual subcell voltages. The most recent development of high-efficiency multijunction solar cells is based on tuning the bandgaps by Solar Junction as shown in Fig. 2, which is reported [57] to have a record efficiency of 43.5%. These cells have the capability to maximize the absorbed sunlight within CPV modules while maintaining a lattice matched architecture and allowing optimal operation under concentrations beyond a thousand suns. Further details about this cell may be found under Wiemer et al. [50].

An ideal solar cell when placed under a CPV system undergoes a series of losses as can be seen in Fig. 3. The ideal performance of a solar cell initially reduces due to some reflection losses of the concentrator and the solar cell; further the errors introduced in the concentrator geometry again tends to reduce the efficiency. The uneven or non-uniform illumination produced by the use of concentrator increases the cell temperature, cell resistance and lowers the efficiency. Almost 40% of energy is lost compared to what it should perform ideally throughout the process. The purpose of the optical system is to concentrate sunlight and direct it to the solar cell uniformly, but this does not happen in

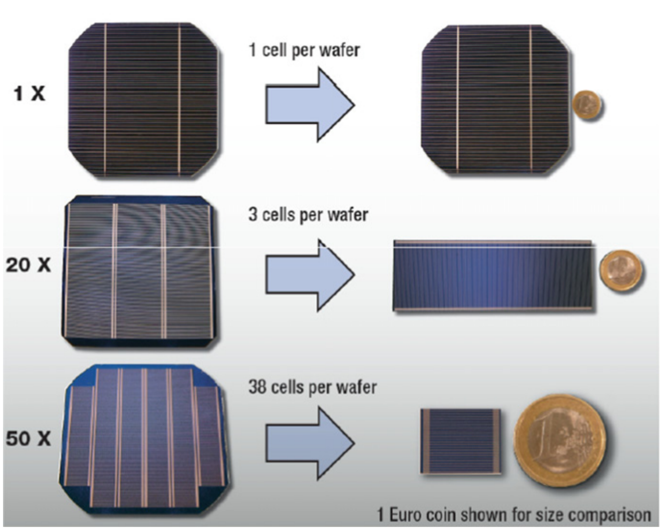

Fig. 1. Comparison of 1Sun and concentrator cells made using LGBC processes (*Picture courtesy: Narec*).

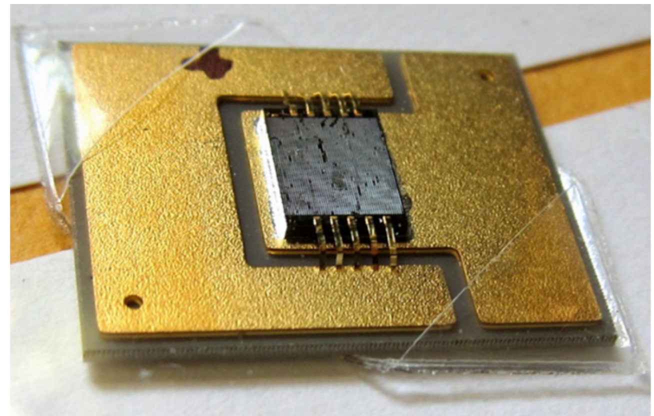

Fig. 2. Multijunction solar cell having a record efficiency of 43.5% by solar junction (*Picture courtesy*: *Jurvetson-flickr*).

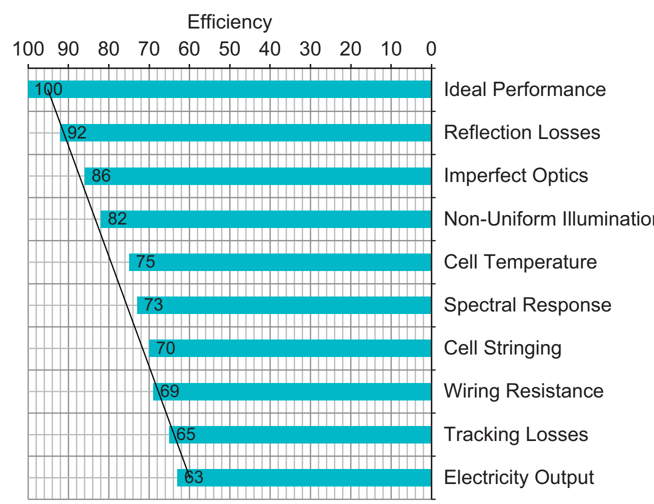

Fig. 3. Losses occurring in the CPV system.

reality as some portions of the solar cell get more exposed and some portions remain not much exposed causing a non-uniform flux distribution on the solar cells as shown in Fig. 4. Only a part of the solar energy is converted to electricity while most of it is dissipated in the form of heat. The presence of non-uniformity increases the temperature across some portions of the cells and causes hotspots which tend to deteriorate the cell performance significantly. Hence, its quantification helps in designing the solar cell appropriately and making proper prediction in its performance. When under concentration, these solar cells produce larger amounts of currents, however this gets limited due to the losses caused by the increase in series resistance. As the concentration ratio of the system increases, it becomes more and more difficult to maintain uniformity of the incident flux on the solar cells.

This paper explores the causes and effects of non-uniformity in CPV technologies, identifies the methods of measuring and predicting it and finally draws methods that could be utilized for reducing its impact on the overall performance of the system.

2. Non-uniform illumination

The use of concentrators modifies the incident radiation on the solar cells, while amplifying it to several times and generating non-uniform illumination patterns which are both discrete and

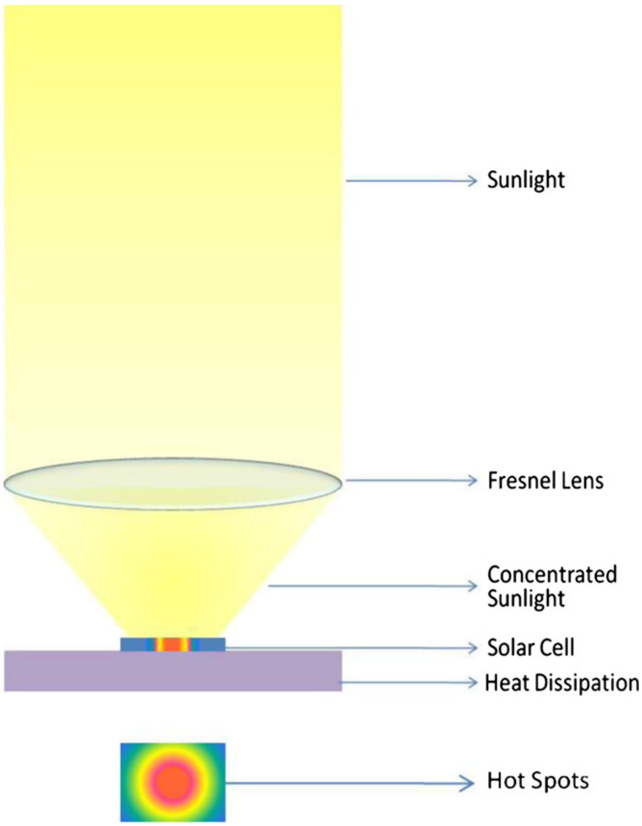

Fig. 4. Hot spot development in the solar cell due to non-uniform illumination in a concentrating system.

discontinuous in nature. Non-uniformity can be caused over a single surface of solar cell subjected to non-uniform illumination or to a series of cells connected together and each being illuminated. There needs to be a distinction in type of non-uniformity caused in the concentrator solar cells [58]. In the first case, there is excessive illumination on some region of the solar cells and some are rarely illuminated. The regions illuminated excessively generate huge currents and get heated. This decreases the electrical output of the solar cell and some areas of the cell do not operate and the generation of cross currents causes dissipation of electrical power. In the second case a complete shadow effect occurring on one of the cells causes the whole series generator to stop supplying energy. Usually solar cells are connected in series in linear concentrators, where the current passing through each cell is assumed to be same. But in reality, there might be lot of difference between the current generated by each cell depending upon the amount of shading. In case of linear CPV systems it was pointed out by Coventry [59] that the current is almost linearly dependent on the incident light, the current in a string of identical solar cells will be limited by the cell with the least illumination. The longitudinal radiation flux profile may be affected by several factors which could include the concentrator shape, size and defects in manufacturing. The cell receiving the lowest illumination might limit the current and the performance of the cells connected in series. The electrical energy produced in the illuminated cells is dissipated in the cell which is not illuminated, and this cell is heated.

In the case of multijunction (GaInP/GaAs/Ge) I–VIII–V cells almost 37% of the energy absorbed in a solar cell is used for generating electric power and the rest 63% dissipates in the form of heat [60]. The cell temperatures could reach more than 1300 °C. The nonuniformity further increases the I^2R losses in the high concentration regions causing the cell to operate at much lower efficiency. Non-uniform illumination typically produces degradation in performance since higher intensities occur near the cell center further from the cell bus-bar, producing increased power losses in the cell front grid and front surface diffused regions of conventional planar cells [61]. The combined effect of non-uniform illumination and surface resistance on the performance of solar cell was described by Vishnoi et al. [62]. It was predicted theoretically and experimentally evaluated that the dark regions in a partially illuminated cell acts as a load responsible for a drop in conversion efficiency, open circuit voltage and short circuit current values.

The non-uniformity arises due to several reasons related to the concentrator design, relative position of the solar cell and the sun, and external factors like shading [58]. The non-uniformity in the illumination affects several parameters of the solar cell ultimately causing a drop in the overall cell efficiency. It is quite challenging to estimate the performance of concentrator solar cells under nonuniform illumination and is simply beyond gathering the data collected by exposing the solar cells to a range of uniform illumination conditions. Some of the most notable causes, effects and methods of estimating or measuring the performance of solar cells subjected to non-uniform illumination on the cell are highlighted below.

2.1. *Causes of non-uniformity of incident flux*

The solar illumination once incident on the CPV system gets concentrated and is incident on the solar cells. The purpose of the optical system is to concentrate sunlight and direct it to the solar cell uniformly, but this does not happen in reality as some portions of the solar cell get more exposed and some portions remain not much exposed causing a non-uniform flux distribution on the solar cells. For cases where there is continuous tracking the non-uniform illumination may be introduced by only the optical element. But in cases where the system is fixed at a particular position the sun's position with respect to the system may introduce inhomogeneity. The electrical performance of the solar cell varies throughout the day depending on its orientation and the flux incident on its surface. It is very important that the solar cells are designed by proper current matching and the incident solar spectrum. Improper design causes increase in the resistance and reduces electrical performance of the system. Xie [6] evaluated the flux distribution along the absorber using ray tracing simulations. Results indicated that uniform distribution of solar irradiance for moderate concentrator ratios helps improve the overall efficiency of the system.

Few of the underlying causes of non-uniformity are listed below.

- ***Concentrator optics***: The concentrator geometry and optics play an important role in determining the flux incident on solar cells. Improper design can lead to non-uniformity of the flux and reduce efficiency. Several types of optical elements are utilized in the CPV systems. Each system tends to produce a different degree of non-uniformity in illumination. Some imaging optics like Fresnel lens have inherent problem of non-uniform illumination which causes the movement of the focus along the cell as demonstrated in Fig. 5. The effect of non-uniformity can be found in all the types of CPV systems. Fig. 6 shows the optical power output through a building integrated concentrating photovoltaic system where the optical concentrator used is an asymmetric dielectric based Compound Parabolic Concentrator (CPC). The concentrator shape is designed to operate for extended [63] periods which tends to produce non-uniformities. Fig. 7 shows the non-uniform

illumination profiles on the solar cell surface in LCPV and HCPV systems.

- ***Shape Errors in concentrator profile***: It is not sufficient to just properly design the concentrator, but it is equally important to manufacture and test the geometry for any errors introduced in it. Non-uniformity is due to concentrator optical and shape errors, which even if they are small would have a significant effect on the flux profile [64]. Usually reflectors when used as concentrators get some shape errors while manufacturing which again could become a cause of non-uniformity due to improper geometry.

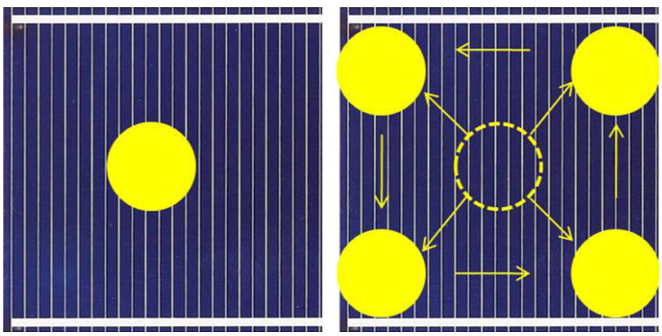

Fig. 5. Shift in the sun focus causing non-uniformity of illumination.

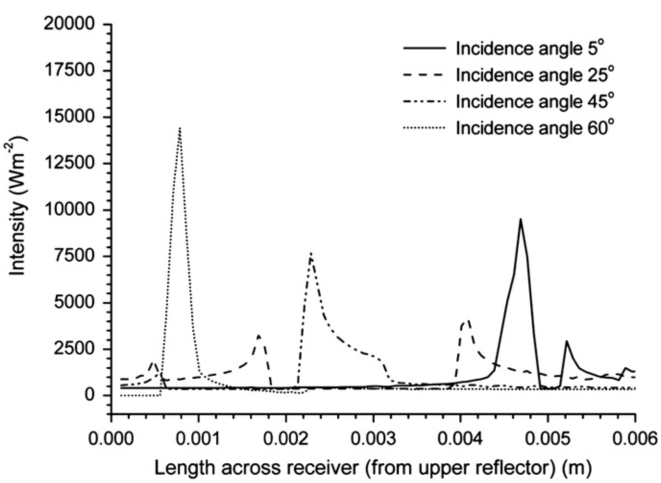

Fig. 6. Flux distribution in LCPV system [63].

- ***Improper tracking***: Concentrating photovoltaic systems are designed in such a way so that the reflected/ refracted sun rays fall exactly on the cells. Improper tracking may cause them to miss their target areas and deteriorate the system. Tracking is mostly required for HCPV applications [45] where it becomes necessary to always keep the solar cells normal to the sun; failure to track the sun properly can again lead to non-uniformity of flux on the solar cells. Although tracking is important but it still cannot guarantee to produce a uniform flux distribution. Franklin and Coventry [65] demonstrated this in the case of a parabolic trough concentrator where the Gaussian flux profile supposed to be in the center moved across the cell. With improper tracking this effect would further be enhanced and the higher flux may move towards the corners of the cell as shown in Fig. 8 and cause further problems. Schultz et al. [66] studied the performance of multijunction cells under uneven illumination caused due to tracking. By performing a raster scan over the subcells using optical fiber connected to a spectroradiometer in the concentrator cell plane, it was found that improper tracking introduced losses due to modified spectral response. Sabry and Ghitas et al. [67] evaluated the non-uniform illumination introduced across the edges due to low tracking accuracy and structure misalignment. An increase in both open circuit voltage and fill factor resulted from shading the edges was found to occur.
- ***Misalignment of concentrator***: In Building integrated applications where the solar cells are placed very close to each other, certain misalignments can occur between the solar cells and the concentrators again causing non-uniformity on the solar cells. In HCPV systems the misalignment of the secondary

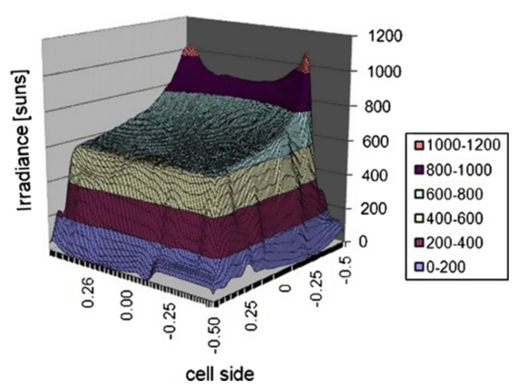

Fig. 8. Tracking induced non-uniform illumination.

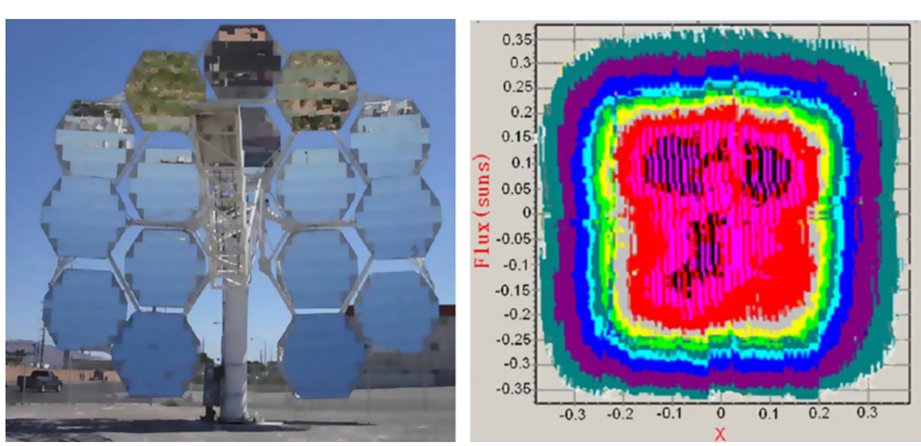

Fig. 7. Flux distribution in high concentrator cells used in a dish concentrator [74].

concentrator tends to reduce the efficiency of the cell significantly as shown in Fig. 9. A significant drop of about 12% was observed in the *Isc* values by Schultz et al. [66] due to the misalignment. Antóna and Sala [68] pointed out the misalignment as a cause of optical dispersion in the CPV system. They evaluated the EUCLIDES type CPV system which consisted of an array of mirrors as the concentrator optical element. The position between each mirror and its receptor was found to be of utmost importance to avoid optical mismatch. Other causes such as wind and weight loads were also found to cause misalignments due to torsion of the structure.

- ***Optical properties***: Several impurities are induced in the optical elements like reflecting mirrors or refractive lens/concentrators. These impurities change the reflective and refractive properties of the concentrating element. Due to which the concentrator behaves abruptly and produces a non-uniform flux different to the one expected at the design stage. The material used in the reflector could also be a cause for the increase in the non-uniformity of the illumination profile. Hatwaambo et al. [69] demonstrated that the use of specular material had higher peaks as shown in Fig. 10 implying more heating as compared with a diffuse material with rolling groves.

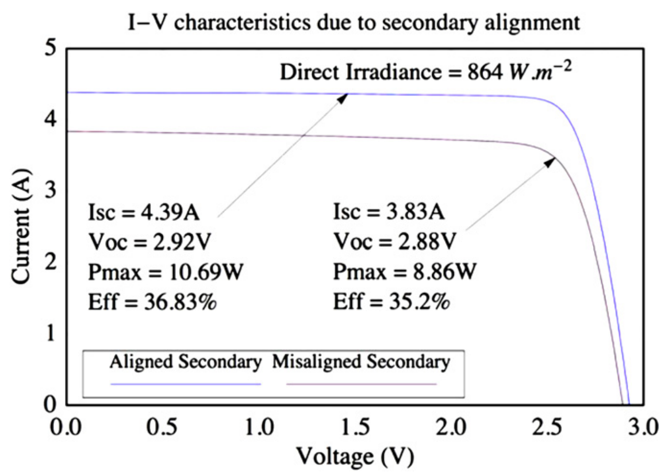

Fig. 9. A 500x geometric concentration multijunction cell experiencing different illumination distribution patterns [66].

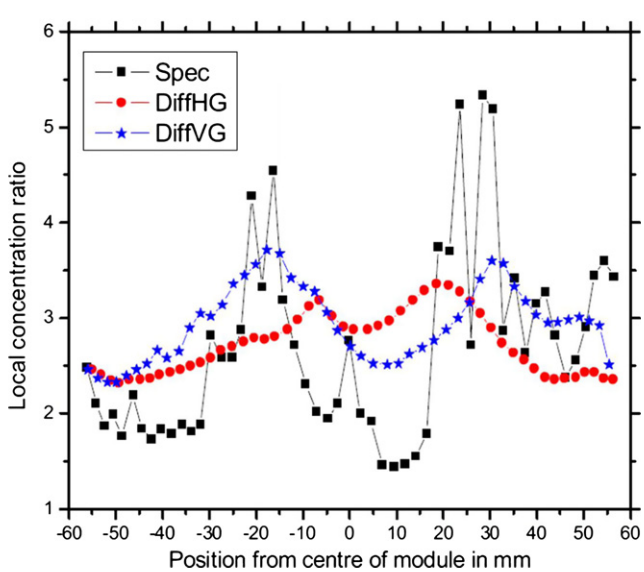

Fig. 10. Peaks in illumination profile while using a specular and diffuse reflector material.

- ***Mechanical failures***: Other than defects introduced while manufacturing, installation or functioning several forms of mechanical failures can occur in a CPV system due to aging; these include loss of transmittance, discoloration of lens or concentrator optics, fracture and mechanical fatigue [70], shape change, buckling, and warping, details of which are provided in [7].
- ***Spectral response***: In the case of multijunction cells, the total photo-generated current densities that can be attained depend on the solar spectrum response of each individual cell. As the solar spectrum changes during the day different subcells limit the achievable photo-generated current density [66]. The performance of the solar cell at a particular day or time is different and varies throughout the period of the year, making it important to understand and optimize the solar cell accordingly. The efficiency of the concentrator cells also depends on a number of factors including its spectral response, diffusion lengths, surface properties, contact method and its configuration [71]. The spectrum of light changes slightly once it passes through the concentrator. The difference in the diffusion lengths between the emitter and base changes the short circuit current and makes it dependent on the incident solar spectrum. The distribution of the generated charge carriers is also dependent on the incident spectrum. It is very important to know the spectral response of solar cells to determine the efficiency under standard rating conditions. Using the spectral response a spectral mismatch correction factor is used to calculate the cell current corresponding to the standard test conditions. Schonecker and Bucher [72] estimated the uncertainty due to non-uniform illumination and its effect on spectral response for different types of solar cells. Recently Victoria et al. [73] analyzed the effects of spectral non-uniform irradiance distribution on multijunction solar cell performance. They suggested that in order to accurately predict the performance of a MJ cell, the absolute and spectral spatial non-uniform irradiance profiles created by the system must be studied. The spectral variation significantly decreases the current generated by one of the subcells which consequently decreases the total current passing through the series of subcells.

2.2. Effects of non-uniform illumination

The nonuniformity in illumination profile causes several problems in the functioning of the CPV system. Some of them are related to the electrical performance of the solar cell, while others are related to the overall performance of the CPV system. The following discussion summarizes the effects in two basic categories of electrical and thermal impacts. It may be noted that some of the electrical parameters get affected as a consequence of thermal effects introduced by the non-uniform illumination profiles thereby reducing the overall system performance.

a. ***Electrical***: The non-uniform illumination produces ohmic drops higher than expected, mainly because the cell operates locally at higher irradiance [75]. In a non-uniformly illuminated solar cell it is found that an internal current flows even in open-circuit conditions, which is directly proportional to the irradiance and the degree of non-uniformity [76]. The parameters that get affected finally reducing the solar cell performance include

total photocurrent

b. cell's short-circuit current

c. cell's short-circuit current density

d. average illumination intensity
e. open-circuit voltage
f. fill factor

In concentrator solar cells, the diffused layer has a very low thickness which is usually about a micron, in the presence of non-uniform illumination the open circuit voltage is affected primarily by the cell area and the sheet resistivity. The non-uniformity produces a gradient in the charge carrier density which causes the lateral currents to flow through the emitter thereby causing an open circuit voltage drop. Gopal et al. [77] studied the effect of non-uniformity on photovoltaic decay and explored the possible mechanisms responsible for the discrepancies between the experimental results and models. They observed a drop in steady-state effective open-circuit voltage under non-uniform illumination, because of its modulation by the surface voltage caused by the sheet resistivity of the emitter region of the solar cells. In a PV cell the maximum current obtained is known as the short-circuit current (*Isc*) and the maximum voltage obtained is known as open-circuit voltage (*Voc*). The value of current corresponding to this open circuit voltage is zero and the value of voltage corresponding to the short circuit current is zero therefore yielding power at both points as zero. Franklin and Coventry [65] studied the effects of non-uniformity on the I–V characteristics of the solar cell both numerically and experimentally. Fig. 11 and Fig. 12 demonstrate the difference in the I–V characteristics of the solar cell when exposed to uniform and non-uniform illumination patterns for both silicon and multijunction solar cells. The parameter fill factor or 'FF' (abbreviated) defines the maximum power that can be obtained using the solar cell and defined as the ratio of the maximum power from the solar cell to the product of *Voc* and *Isc*. The value of the fill factor in the modeled cell differs from that of the reference cell at the same number of suns because of different losses in the metal grid [78]. These differences result from the non-uniform illumination profile and different grid design. The effect of concentration distribution on the cell performance was studied by Goma et al. [79] while using a 3-d lens as a concentrating element. The fill factor was calculated as a function of sheet resistance under both uniform and non-uniform irradiation. It was found that the non-uniform simulation results agreed well with the real conditions as shown in Fig. 13, and was more pronounced with increasing sheet resistance values (higher series resistance). Herrero et al. [80] studied the effect of non-uniformity on multi-junction cells and found that the fill factor decreases with an increase in non-uniformity. They attributed this drop to the increase in series resistance losses which further translates into fall of the solar cell efficiency. Araki and Yamaguchi

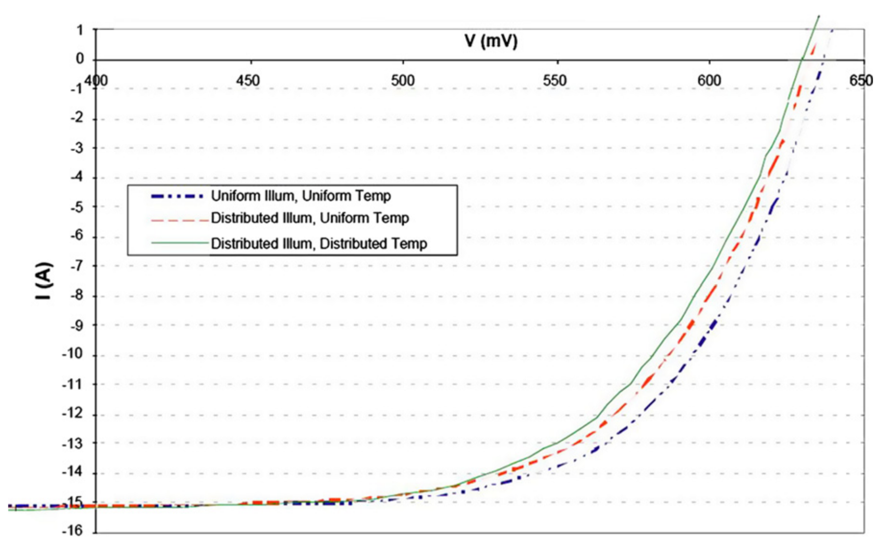

Fig. 11. Difference in IV characteristics of a Si solar cell exposed to a uniform and non-uniform illumination [65].

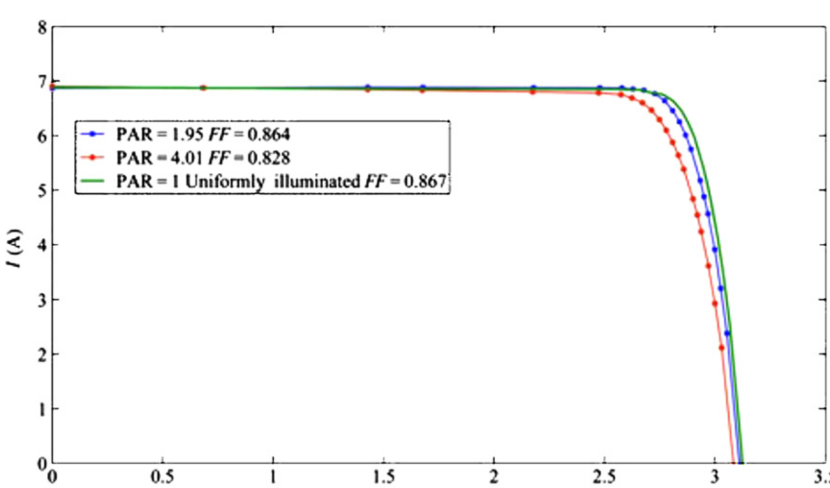

Fig. 12. Difference in IV characteristics of a multijunction solar cell exposed to a uniform and non-uniform illumination [80].

[81] presented a calculation method showing the cause for the non-linear diode behavior of multi-junction concentrator cells due to the presence of non-uniform illumination. The method identified an increase in ideality factor due to the presence of non-uniformity. They also pointed out that the presence of non-uniformity significantly dropped the fill factor. They modeled the interaction between the chromatic aberration and non- uniform flux distribution and simulated its effects on the Solar cell performance as shown in Fig. 14. Usually the fill factor is expected to improve due to the presence of chromatic aberration at the cost of low *Isc*, but it was found that the recovery of FF by chromatic aberration was not sufficient to cancel the damage caused by the nonuniform illumination.

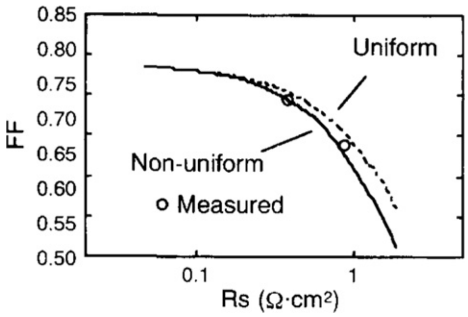

Fig. 13. Effect of non-uniformity in illumination profile on the fill factor [79].

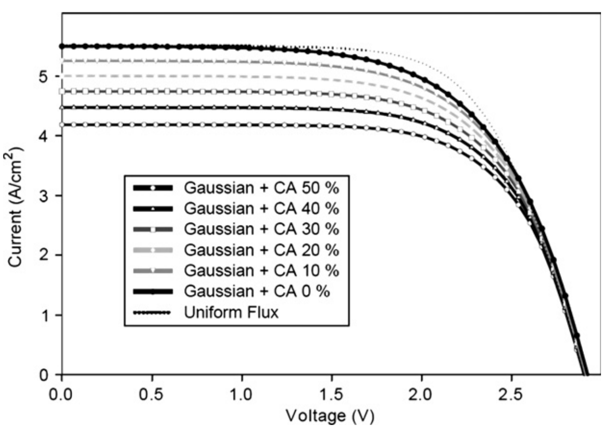

Fig. 14. Effects of non-uniform illumination with chromatic aberration in a 3-junction solar cell.

- ***Thermal***: Concentrating sunlight onto small solar cell produces localized thermal heating. The characteristics of the illumination optics determine the illumination distribution across the cells, this could heat the cell along the surface causing degradation in its performance and cause non-uniform temperature profiles across the cell area [61]. In multijunction cells different layers of the cell absorb different spectra of light producing a temperature gradient along its depth in addition to the temperature gradient along its surface. The power dissipated from the solar cell plays a major role in determining the solar cell performance as only a part of the incident solar radiation is converted into electricity and the remaining is converted to heat. The concentrator solar cells are subjected to high amounts of radiation and so need a passive or active cooling mechanism to maintain lower operating temperatures. The heat dissipation from the solar cell ensures proper working and increases their life-time and decreases the wear caused by excessive temperatures. The solar cell performance is very much related to the series resistance caused by its components, which depends on the cell base, emitter area and the amount of metal used in the grid design [78]. The operational cell temperature is usually determined by means of V_{oc} versus temperature data. The high flux level in concentrating systems along with non-uniformity affects this dependence and introduces some errors in measurements. Anton

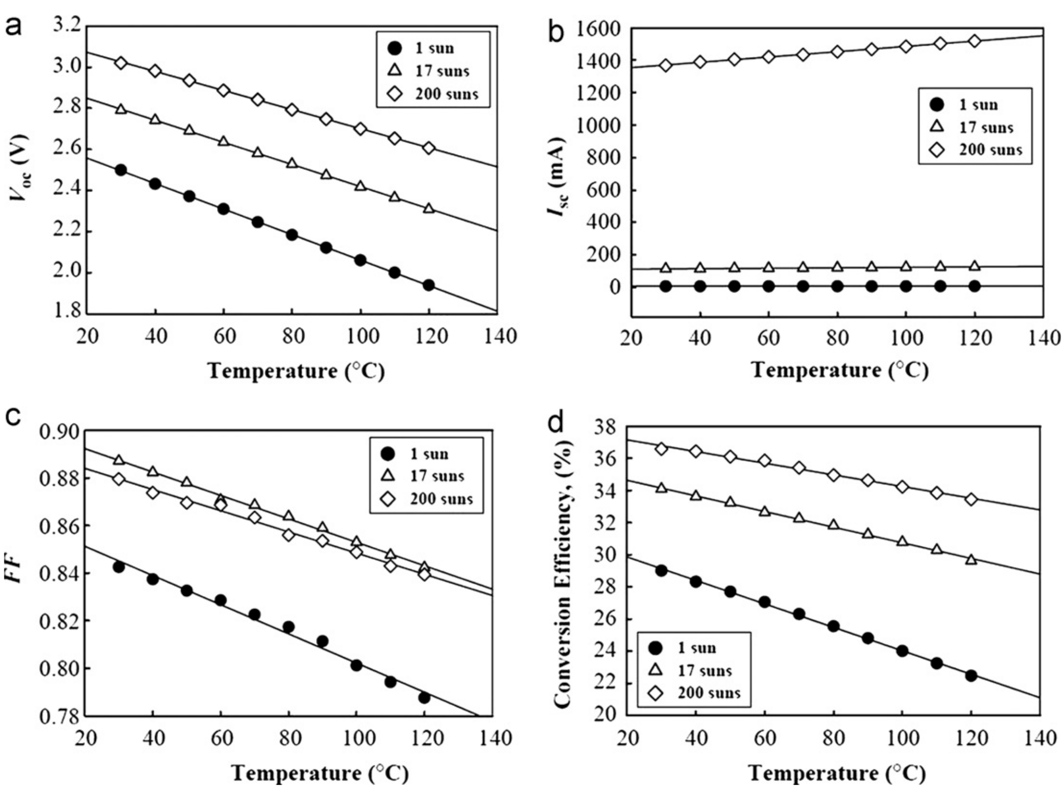

Fig. 15. Variation of electrical characteristics with temperature for a triple junction solar cell adapted from [84].

[82] experimentally validated and introduced a relation between maximum cell temperature and open circuit voltage for a particular concentration level. In their review Royne et al. [83] pointed out the non-uniform flux distributions over the receiver surface generally having a peak flux higher than the mean value at that concentration level, therefore requiring a cooling device capable enough to handle these peak intensities throughout the cell surface. Nishioka et al. [84] evaluated the temperature dependence of electrical characteristics i.e., temperature coefficients of V_{oc}, I_{sc}, FF and efficiency for InGaP/InGaAs/Ge triple junction solar cells as shown in Fig. 15. It was found that the temperature dependence of efficiency is mostly affected by the dependence of *Voc* on its temperature coefficients. The efficiency was found to increase with increasing Concentration Ratio (CR) due to the rise in *Voc* but again found to decrease with rise in the cell temperature. However, lesser impact on efficiency was observed at high concentrations.

CPV technologies are currently evolving, which makes it difficult to predict their reliability for longer periods of time. However to overcome this shortcoming accelerated tests are performed. Recently [85] thermal aging tests for concentrator photovoltaic solar cells and systems under illumination were deployed for more than 10000 h in a thermal aging tester while forward biasing the solar cells at the required current. The thermal effects of the non-uniformity are more pronounced in case of HCPV systems, however it is equally important to be studied for both LCPV and MCPV systems.

2.3. Importance for the industry

CPV technologies are continuously undergoing developments. In order to match these developments in concentrators it is very important that the industry have certain capabilities to interlink the cell design with different kinds of concentrators and their optical performances. There exists a need for an effective cell design model to ensure good conversion efficiency over the required concentration range, illumination patterns and variety of cell sizes as the ultimate aim of the system is to reduce the $/watt of electricity produced. Fig. 16 demonstrates the non-uniform illumination in the solar cell of a Whitfield Solar trough (vintage, 2006), with the end removed to aid viewing inside. It shows the Fresnel lens at the top of the image and the resulting light spot that is formed by the Fresnel lens on the Narec LGBC silicon concentrator cell. This is a typical image of the spot size in the Whitfield collector, as it gives a generous allowance for tracking error. Inside the illuminated spot the illumination will not be uniform. If a 'classic' imaging Fresnel is used, the resulting spot has a very peaky distribution across it. Whitfield Solar and their lens supplier modified the lens facets to get as even an illumination as possible within the spot, but even so the distribution obtained was certainly not a pure 'top hat' shape and a more like 2:1 from average to peak illumination was observed.

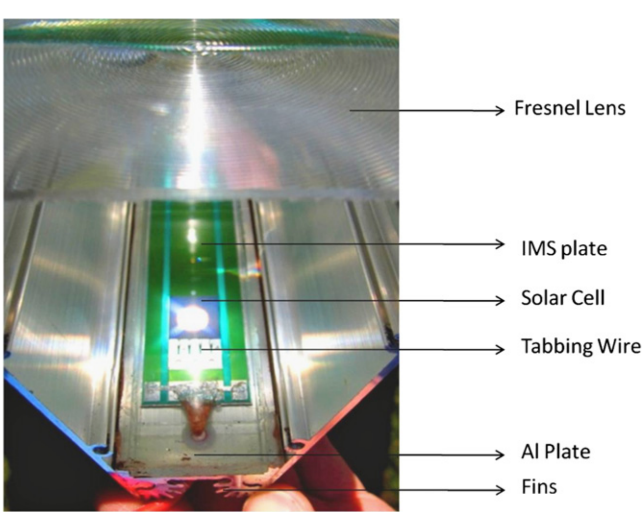

Fig. 16. A cut out view of CPV system by Whitfield Solar (*Picture courtesy*: *Whitfield Solar*).

A drop in solar cell efficiency due to non-uniformity reduces the amount of power produced and thereby tends to increase the cost of power produced per watt. Consolidation of an optimized design into processes capable of rapid throughput at reduced costs is sought to ensure means to process and evaluate cells with the properties needed as per the requirements [86]. Solar cell manufacturers have the capability of tailoring the solar cell design in order to match the illumination patterns of the CPV system. A few examples demonstrating the capability at Narec to modify the cell architectures is shown in Fig. 17. These include cell architectures with (a) cell, with single long busbar, (b) cell, with two bus bars at the cell short edges, (c) trench cell having a series of busbars equally spaced throughout the cell. Several companies are using these types of cells and are targeting costs of 10 USD cents per kWh using CPV technology [87]. Examples of some of the recent prototype cells produced at the Narec PV Technology Centre for the ASPIS concentrator [88] are also shown in Fig. 18.

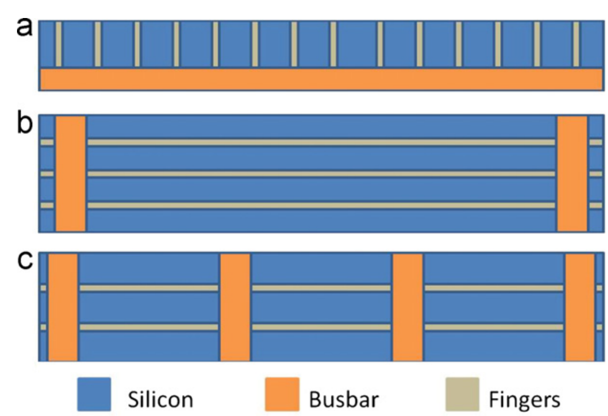

Fig. 17. Grid patterns in solar cells.

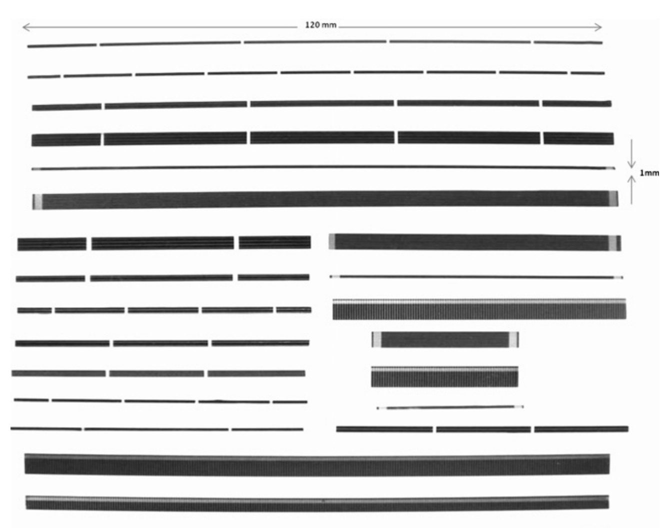

Fig. 18. Sample sized solar cells made for CPV applications.

2.4. Economics of CPV and dependence on non-uniformity

The economics of CPV operation essentially depends on several factors. The total system design includes concentrator design, cell design, thermal management, tracking and peak power handling capability within the solar cell. CPV is an attractive option to increase the electric energy output while reducing the technology and power production cost. However, the effect of non-uniformity of the incident solar radiation and the higher operating temperatures could reduce the efficiency of electric conversion and decrease the lifetime of solar cells, thereby changing the whole equation used to calculate payback period of the CPV system. The effect of non-uniform flux could lead to drop in performance of a system by a certain percentage which is not calculated or predicted while making system calculations. The non-uniformity may very well then further increase the price of the power produced using CPV making it not profitable in the long term. Recently Dai et al. [89] pointed out that a number of investigations and research have been focused on performances and designs of solar cells with concentrators; however little effort has been made to study and analyze this problem in detail. Therefore it is very important to understand the impact of non-uniformity on a case by case basis and include its effect while making long term predictions or calculations of the CPV technology. At the same time methods to measure this effect accurately and reduce its impact need to be explored for the overall benefit of the CPV industry.

3. Concentrator solar cell characterization and testing

Generally the characterization of concentrator solar cells is carried out under uniform illumination conditions. However, in reality these cells are exposed to non-uniform flux in working conditions. The illumination flux on the solar cell can have a profile very different to the one produced by using a concentrator when compared to the uniform illumination conditions used to carry out the cell characterization.

3.1. Modeling of solar cell subjected to non-uniform flux

The modeling of solar cell under non-uniform flux plays an important role in the development of CPV based technology. Modeling can prove to be a very valuable tool to optimize the solar cell design for particular application conditions based on the available solar spectrum, the concentration ratio of the system and the optical concentrating element. It helps in deciding on the material characteristic required, doping to be applied and the layer thicknesses for attaining optimum operating efficiency. The advantage of having such a model is that it helps in exploring the performance of different concentrator and cell combinations using cells of various types, shapes, color, sizes and metallic grid design, with or without a secondary optical cover, under different conditions. Mitchell [90] analyzed two different cases of non-uniform illumination to examine trends in behavior of solar cell performance. In both the cases the flux was assumed to be a cosine function with maximum value of flux along the bus bar in the first case and zero in the second case. It was found that the shape of the illumination profile had no effect on the ideal conversion efficiency modeled without series resistance when compared to the case of uniform illumination. However, when the series resistance was modeled a significant drop in cell conversion efficiency was observed in the case where the minimum flux is assumed along the bus bar. It was concluded that the effects of the non-uniformity of the flux profile may be mitigated by incorporating a lower top layer resistance. Also it was predicted that low top layer resistance can have a number of economic benefits for concentrator systems with reduced power losses in concentrating solar cells and lower impact of the non-uniformity in the illumination. Chenlo and Cid [91] studied the thermal and electrical characteristics of a solar cell with cooling mechanism subjected to both uniform and non-uniform illumination at a concentration of 24x using a Fresnel lens. On comparing the best cell efficiency of 17.2% at uniform illumination with the module best cell efficiency a drop of almost 6% is observed due to the combined effects of cell temperature rise, lens losses and non-uniform illumination. Using detailed models a parametric study was carried out to study these effects and it was found that the system losses are higher from the combined effects of non-uniform illumination and temperature, than from the sum of both effects taken independently.

The most commonly applied method to carry out the electrical simulation is to divide the cell into smaller subcircuits representing different parts of the solar cell and model every subcircuit by an electrical circuit as described by one diode with distributed diode effect [65,92–95], two diode [96–98], or three diode model [75]. The lateral resistances in the cell lead to a voltage drop across the cell surface causing different points on the cell surface to operate at different voltages and therefore produce different current densities; this phenomenon also known as distributed diode effect was considered while modeling by [94]. While considering this phenomena the current from each row of unit cells flows to the contact grid bar, where it adds to the current contributions of the other rows. The voltage drops due to series resistance along the row of unit cells are additive, and the voltage drops along the contact bar are additive [90].

Luque et al. [75] investigated the temperature distribution in a concentrator solar cell under non-uniform illumination considering the cell to be electrically isolated from the heat sink. Representing the cell as three distinct diodes, separated by resistors the cell is modeled to evaluate the effects of non-uniformity in flux and temperature. The nonuniformity was found to reduce the system operation and increase the temperature and series resistance thereby reducing cell efficiency. A simplified representation of the electrical circuit model of the solar cell is represented in Fig. 19. The term I_d represents the dark current and the term I_{ph} represents the photo-generated current. The total current flowing in the external load R_L is given by Eqs. (1.1) and (1.2). The term I_o represents the reverse saturation diode current corresponding to the diffusion and recombination of electrons and holes in the p and n sides of the cell, V is the mean cell voltage across the external load resistance R_L and V_T is the thermodynamic voltage, V_j is the junction potential, k_B is the Boltzmann constant, q is the electron charge and n is the ideality factor which is usually greater than 1.

$$I = I_{ph} - I_d \quad (1.1)$$

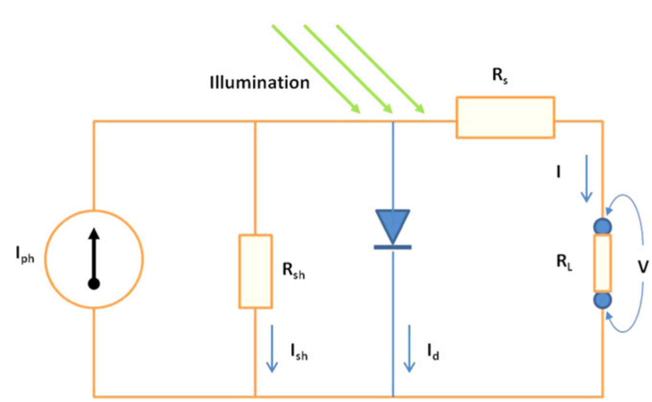

Fig. 19. Equivalent circuit of solar cell.

$$I = I_{ph} - I_o\left[\exp\left[\frac{V_j}{nV_T}\right] - 1\right] - \frac{V_j}{R_{sh}} \tag{1.2}$$

$$V_T = k_B T/q \tag{1.3}$$

$$V_j = V + IR_s \tag{1.4}$$

Eq. (1.2) is of general form, it may further be reduced depending on the emitter region I_e and the dark or finger region I_{da}. The term I_{ph} strongly depends on the illumination and is directly proportional to its intensity.

$$I_e = I_{ph} - I_o\left[\exp\left[\frac{V_j}{nV_T}\right] - 1\right] - \frac{V_j}{R_{sh}} \tag{1.5}$$

$$I_{da} = I_o\left[\exp\left[\frac{V_j}{nV_T}\right] - 1\right] - \frac{V_j}{R_{sh}} \tag{1.6}$$

The incident solar radiation leads to the increase of the temperature of the solar cell which further increases the population of electrons exponentially enhancing the dark saturation current. The dependence of the saturation current on the temperature [99] is represented by Eq. (1.7) which suggests that its value increases with temperature but decreases with increasing material quality. The terms I_{oo} and E_{go} represent the saturation current and the band gap energy at 0 K and are both approximately constant with respect to temperature.

$$I_o(T) = I_{oo}T^3\exp\left[\frac{-E_{go}}{k_B T}\right] \tag{1.7}$$

Using the above basic equations the solar cell can be modeled; however different approaches have been adopted by different researchers to analyze the effects of non-uniformity. Franklin and Coventry [65] modeled the effect of nonuniformity by considering a Gaussian illumination over the cell. In order to obtain the solution, they used a quarter finger space unit of the cell as shown in Fig. 20 and solved equations similar to the ones shown above. Chemisana, Rosell, Mellor et al. and Domenech-Garret [93–95] in their studies applied extended forms of these equations to model one complete finger space unit as shown in Fig. 21. According to [99] Eq. (1.2) may further be expressed as follows for which different forms were applied by Chemisana, Rosell, Mellor et al. and Domenech-Garret [93–95]:

$$I = C_1 G + C_2 T^3 \exp\left[\frac{-T_1}{T}\right]\left(\exp\left[\frac{V_j}{nV_T}\right] - 1\right) + C_3 V_j \tag{1.8}$$

Several profiles have been modeled to understand and predict the effects of non-uniformity on the solar cells. Garner and Nasby [43] developed a computer code to study simple profiles demonstrated in Fig. 22. The method involved solving Poisson's equations for each point on a grid generated on the surface of solar cell. The results were verified against experimental studies. The

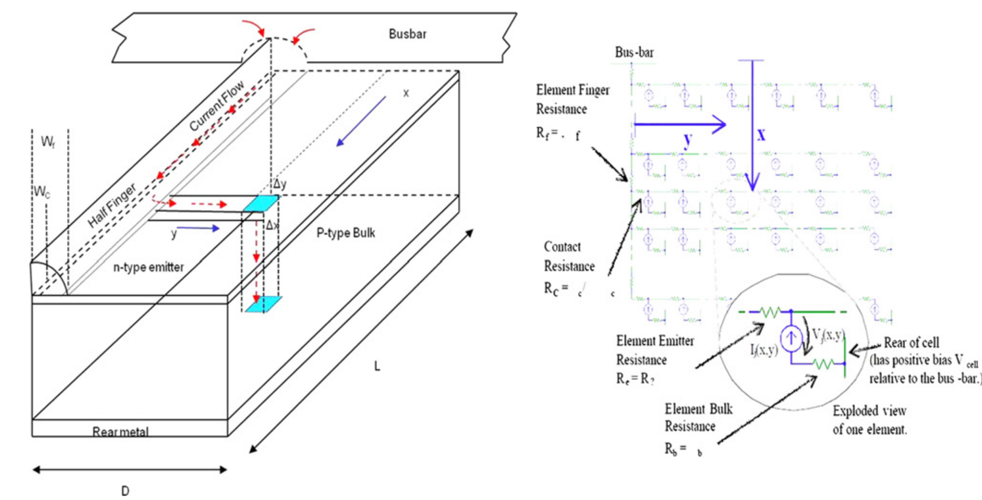

Fig. 20. Quarter finger space cell unit modeled by [65].

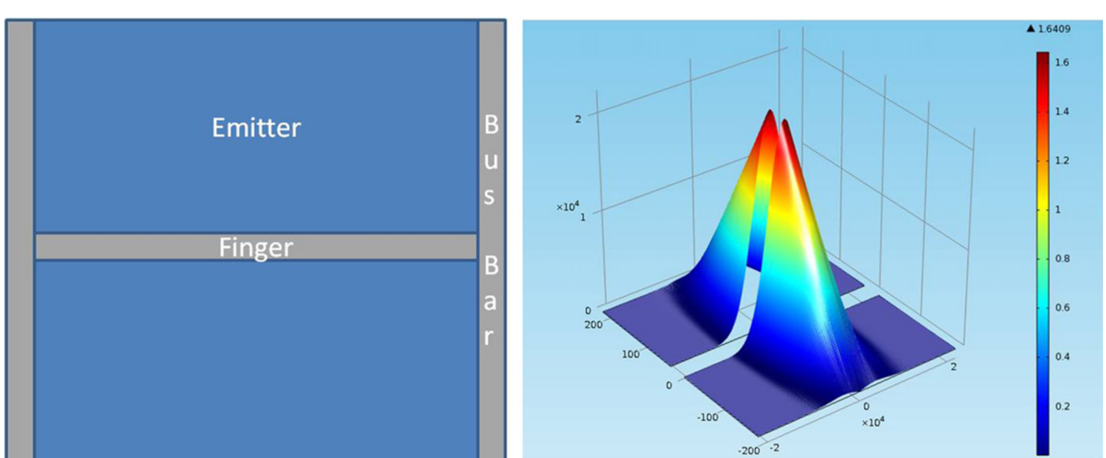

Fig. 21. Full finger space cell unit and current density distribution in a Gaussian illuminated solar cell.

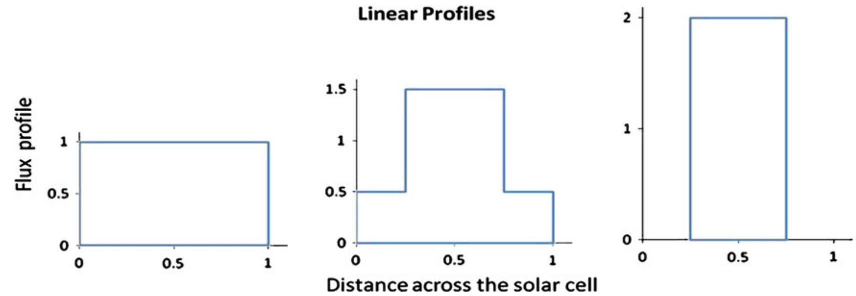

Fig. 22. Different linear profiles studied by [43].

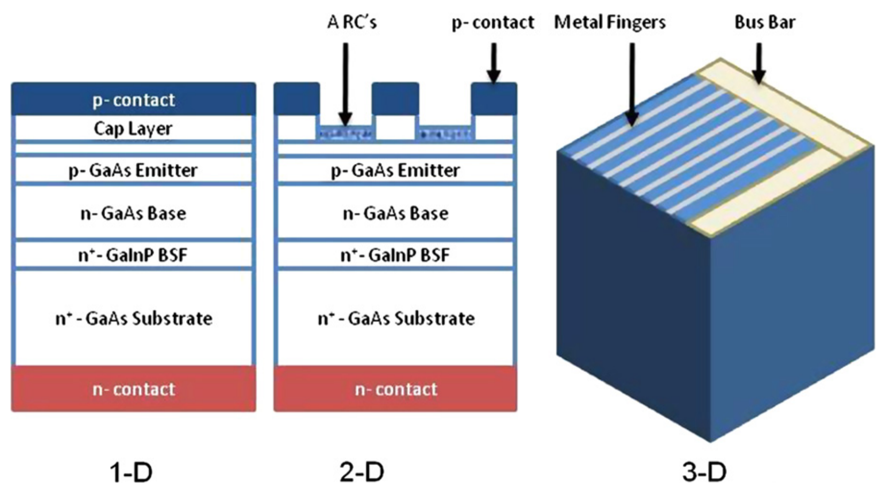

Fig. 23. Types of theoretical analysis considered for modeling solar cells.

concentration values were calculated as a function of the illumination profiles and concentration. Results showed that the efficiency of the solar cells under uniform concentration increases to a maximum till ~30 suns and then decreases. However in the case of non-uniform illumination the cell has maximum efficiency at low concentrations and drop occurs with increased concentration.

Beatriz Galiana and Galiana[97,100] developed a three-dimensional (3-D) distributed model using PSPICE software for concentrating solar cells based on elementary units made up of electrical circuits. This model is capable of optimizing the front metal grid and can help to determine the different causes of series resistance and finally can predict the behavior of a solar cell under nonuniform illumination for single and multijunction cells. A comparison of both one-dimensional (1-D) and 3-D models has been presented in Beatriz Galiana [97], using the model of distributed circuits as shown in Fig. 23. They studied the optimum front grid design for solar cells under 500x, 1000x and 2000x concentrations, results were compared with 1-D models. It was concluded that 1-D models miss out on several details like ohmic effects and alternative current paths that arise at high concentration leading to a non-optimum design. It was concluded that a 3-D model is essential when modeling cells under high concentration. Olson [101] modeled the currents spreading behavior under non-uniform irradiance in MJ solar cells. They pointed that the non-uniform illumination can be a major problem for tunnel-junction interconnected III–V MJ cells if the resulting local photocurrent exceeds the peak tunneling current density and can be mitigated via current spreading.

Algora et al. [102] highlighted the pending issues in modeling solar cells subject to concentration, they used ATLAS simulation software from Silvaco based on TCAD to do 2-D modeling of the effects of nonuniformity in high concentrating CPV cells. However, it was suggested that a 3-D model is necessary to model the concentrator solar cells, especially for the cases of high concentration to demonstrate the effect of non-uniformity. Kerschen and Basore [78] describes an approach for estimating the performance and optimization of a concentrator cell as a function of its metallization using PVOPTICS software. Direct measurements of the flux profile are presented Coventry et al. [92] along the length of a single axis tracking trough. They used OPTICAD to carry out the ray tracing and carried out experimental measurements with a new custom built measurement device. Steiner et al. [96] recently studied the influence of the nonuniform illumination profile combined with a specific tunnel-diode characteristic on the I–V curve of a triple-junction solar cell.

3.1.1. Use of finite element modeling

Finite element method could be very well employed to model the solar cells under both uniform and non-uniform illumination. Mellor et al. [94] developed a two-dimensional (2-D) finite element model for the front surface of solar cell to demonstrate the reduction in fill factor and open circuit voltage as a result of non-uniform illumination. Results showed that the cell operating at open circuit region under a Gaussian illumination profile produces internal currents which flow from the central highly illuminated regions of the emitter to the darker edge regions. The efficiency of a cell operating under illumination with a peak illumination ratio of 10 and average illumination of 12 suns is shown to decrease by more than 1.7% when compared to a cell operating under a uniform illumination under similar conditions. Domenech-Garret [95] studied the PV cell behavior under the influence of combined profiles including Gaussian, inverse Gaussian and off centered Gaussian profiles of non-uniform temperature and radiation using a finite element model using COMSOL software. They combined direct Gaussian temperature and radiation profiles, with several temperature amplitudes as a

moving function. Results showed that the temperature profile spoils the fill factor (FF) although the value of open circuit voltage (*Voc*) remains unchanged for the case of a Gaussian temperature profile with the same short circuit current (*Isc*) value. It was concluded that the Gaussian temperature profile decreases the maximum power value of a solar cell by about 4%. In a recent study by Chemisana and Rosell [93], finite element modeling was carried out to evaluate the performance of a Gaussian illuminated cpv cell under the influence of different temperature profiles. The study was experimentally validated by preparing a proper heat sink to generate the Gaussian and anti Gaussian temperature profiles, which were again simulated to analyze the solar cell performance.

In the studies by Chemisana and Rosell, Mellor et al. and Domenech-Garret [93–95], the finite element model was prepared to solve the continuity equation of space charge as shown in Eq (1.9). While applying appropriate boundary conditions for the cell element shown in Fig. 24. Further details on modeling may be found in respective research articles and are along similar lines described in previous sections.

$$-\nabla(\sigma\nabla V - J^{e}) = Q \tag{1.9}$$

In their study applied a constant temperature condition and a temperature profile condition while solving the problem. Temperature coefficients were also evaluated to accurately model the impact of the temperature profile on the cell performance [93].

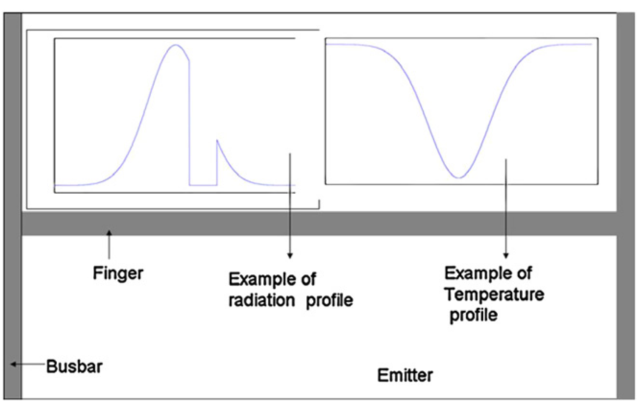

Fig. 24. Showing the Gaussian profiles of illumination and temperature [95].

3.2. Experimental characterization of concentrator solar cells

In order to evaluate large numbers of concentrator cells necessary for production runs, an indoor test facility is needed [86]. Concerns over the performance measurements techniques for the concentrator solar cells have been expressed over several decades [61], since these Concentrator solar cells operate in a high irradiance environment which is very different from the usual one sun conditions under which typical solar panels work. The high irradiance leads to increased sample currents, produces difficulties in maintaining and measuring cell temperatures and causes problems in accurately determining the total illumination power incident on the cell with the added disadvantage of having a non-uniform illumination. The measurement of concentrator solar cell characteristics is a difficult task. Usually a large area pulse solar simulator is used to carry out the measurements, and is capable of recording data every few milliseconds. While performing the experiment the *Isc* at a 1 sun concentration is used as a reference to predict the performance at N suns. Concentration ratio is assumed to be a ratio of I_{sc} obtained at any concentration to the short circuit current at 1 sun. This process assumed a linear behavior of I_{sc} with the concentration. It was found that this method is only favorable at low concentrations by Scheiman et al. [103] and some improvements were presented to provide additional geometrical aids to determine the concentration level and linearity of the solar cell with both experimental and mathematical results.Cuevas et al. [76] demonstrated experimentally the importance of measuring the photogenerated current and open circuit voltage characteristics under the influence of nonuniform illumination. Andreev et al. [104] simulated the different light intensity distributions and carried out I–V curve measurements for GaAs solar cells. It was found that the nonuniform irradiance has an effect on the concentrator cell temperature coefficient. They studied the combined effects of temperature and flux distribution on high concentrator cells using a flash tester, light guiding elements and a built in heater. Results showed the importance of coupling both temperature and flux distribution effects while optimizing the solar cell. They also highlighted their importance in the value of temperature coefficients of the fill factor which help in making the right choice of the cell structure and the grid configuration. Schonecker and Bucher [72] pointed out the influence of spectral response and nonuniform illumination on solar cells. During the testing of solar cells monochromatic

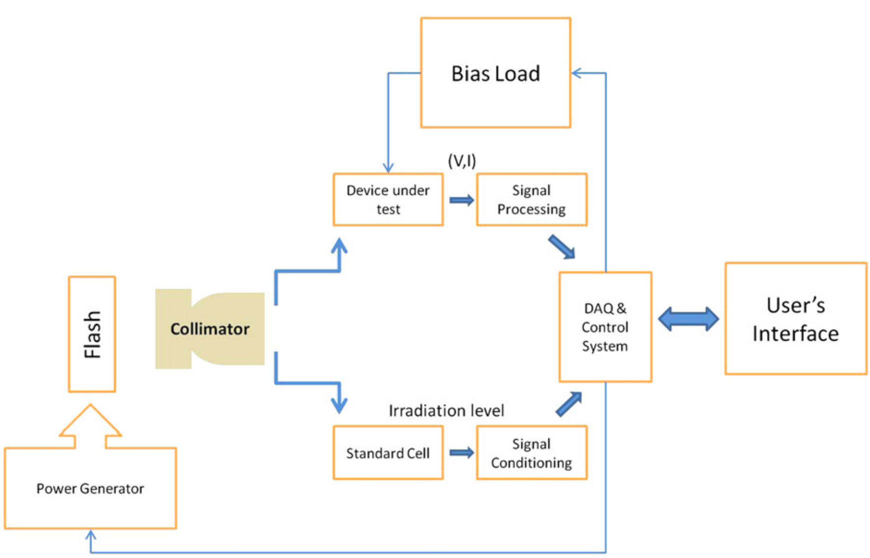

Fig. 25. Showing the block diagram of IV-100 system used by [107].

source is used, and if the test cell area is large it is found that only a part of the solar cell gets illuminated leading to an error due to the difference in the local spectra response of the solar cell under the impact of actual conditions. They used three different setups to measure the influence of the nonuniform flux and spectral response on solar cells. It was concluded that the inhomogeneity caused on the cell area while testing under uniform illumination can be controlled by carrying out measurements against a reference cell of equal size to that of the test cell. Sinton and Pauley [105] developed a new method for measuring the I–V characteristics of solar cells making use of a series of short pulse of light with different intensities under steady state ensuring that it would resemble performance under actual sunlight which varies throughout the day and each day every year. Using this method a variable voltage is applied to the solar cell during a light pulse to measure the instantaneous current at a given voltage and light intensity. Shimotomai [106] developed a method and apparatus for measuring I–V characteristics of solar cells having an improved irradiance on the solar cell test plane. Using a means of adjusting irradiance the solar cell placed on the testing plane is divided imaginarily into a number of sections and a selected member for adjusting irradiance is disposed opposite the test plane to equalize the irradiance level at every section. Katz et al. [107] demonstrated the use of an high flux-test facility that allows the localized irradiation to be replicated using a parabolic mirror and a optical fiber that guides the concentrated solar irradiation to the concentrator solar cell located indoors. Using this method, almost the same spectral output of localized irradiation can be generated. New equipment IV-100 as shown in Fig. 25 was developed [108] to measure the I–V characteristics of concentrator solar cells under non-uniform illumination. This system mainly consists of a flash lamp capable of reaching high irradiance levels of up to 200 suns. Using photolithography, masks were made replicating the flux patterns produced by using concentrating elements as shown in Fig. 26. The effect of non-uniformity in illumination and temperature was studied experimentally by Lu et al. [109]. In their study, they made use of a non-uniform factor (α) to describe the non-uniformity of illumination. Higher factor indicates higher non-uniformity. It was found that both FF and maximum power reduced with increasing α values and a relationship was developed with the use of another proportionality constant β. While correlating β for different temperature and illumination profiles it was found that the effect of nonuniform illumination could be considered equivalent to a certain degree rise in temperature values. It was concluded that the non-uniform illumination raises the temperature of the cells and induces a nonuniform temperature gradient across the cells causing a nonuniform power loss and then causing a power degradation of the complete CPV system. Herrero et al [80,110] developed an indoor procedure based on a CCD camera to characterize different illumination patterns produced by Fresnel lens and secondary optical elements. Further, they reproduced these patterns using masks as shown in Fig. 27. These masks were prepared by a high resolution photoplotter and performed experimental evaluation of the influence of nonuniform illumination on the solar cell performance. Fig. 28 describes the methodology adapted, where the illumination profiles are captured using the CCD camera, and reproduced on masks, which are placed above the solar cells and their effects of nonuniform illumination is analyzed. Using a parameter PAR (Peak to average ratio of the Gaussian profile) the different illumination profiles were defined and tested in a solar simulator by placing these masks over the cells. These methods of evaluating the efficiency lead to results which were close to the actual optical system.

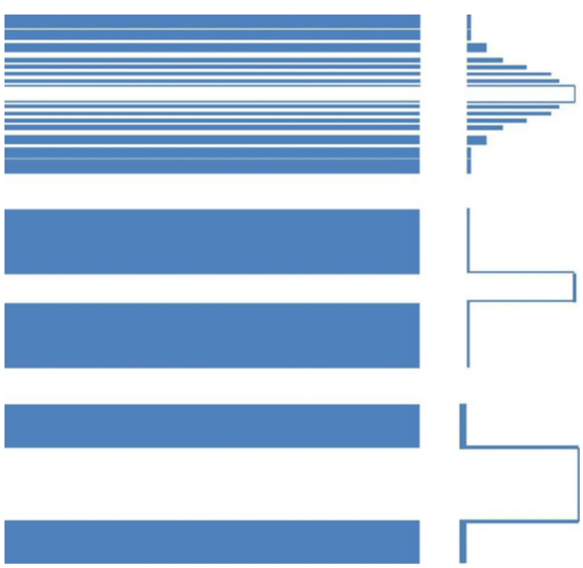

Fig. 26. Photolithographic masks for different illumination patters used by [107].

3.3. Optimization of the flux profile on solar cells for CPV

The nonuniformity in illumination is associated with a decrease in the conversion efficiency. However, there are few cases where it could actually help in improving the performance of the concentrator solar cells. This could be basically related to the type of the flux profile of the incident radiation. A profile with high intensity close to bus bars [90,111] has been found helpful in improving the performance. However, if the non-uniform irradiance distribution could be adequately chosen, even higher efficiency levels would be attainable. Benitez and Mohedano [111] studied the problem of calculating the flux pattern that maximizes the efficiency of a cell for a given average concentration factor and presented an approximate expression to measure the cell power output difference between the optimum and nonoptimum illumination profiles at a given voltage. Huang et al. [45] developed a computer program to simulate the flux distribution for a concentrator employing Fresnel lens. Results indicated that the uniformity could be largely improved when the receiver plane is placed somewhat upwards or downwards from the focus. However this could reduce the concentration ratio of the system significantly. The design and optimization of a concentrator solar cell is a result of

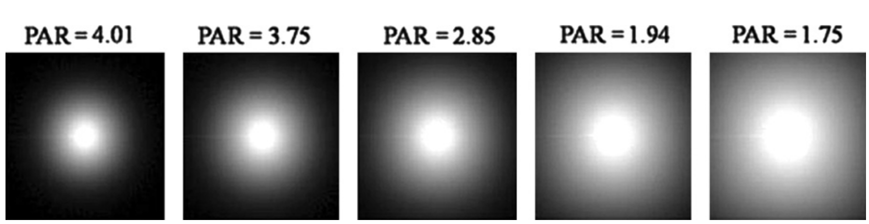

Fig. 27. Masks used to perform indoor characterization.

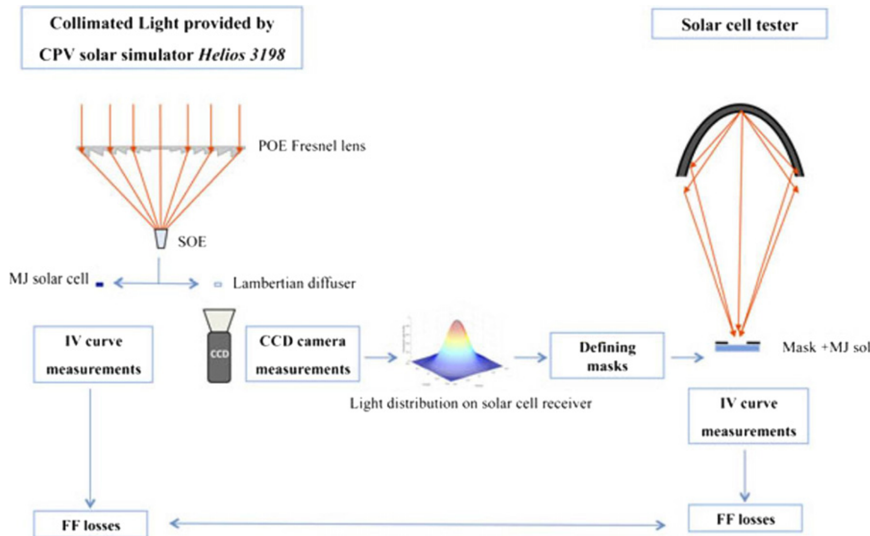

Fig. 28. Methodology followed to characterize the illumination profiles and perform experiments on the solar cells using masks.

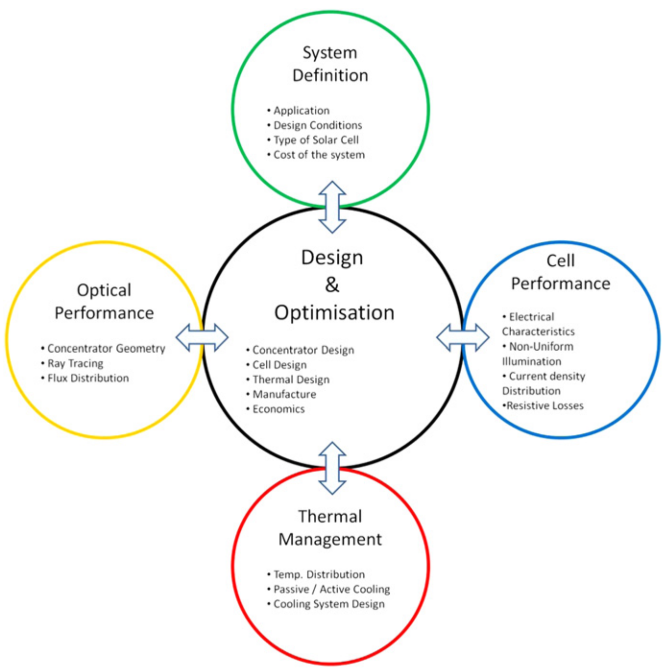

Fig. 29. Optimization cycle for a solar cell design.

several compromises between different challenging mechanisms as can be seen in Fig. 29. Optimizing one parameter could affect the others that may be equally important to improve the efficiency of the solar cells. A key list of information needed for a CPV design is the type of application, where it is to be installed, type of solar cells to be used and finally the expected cost of the system. Based on this information, the type of concentrator and its geometry can be identified. Based on ray tracing the optical performance of this concentrator geometry is evaluated, fine tuning the geometry may be required in order to improve the performance or reduce the amount of material used for the concentrator manufacture typically the CPC's if used are truncated in order to have a balance between the amount of material and optical performance. Based on the optical analysis, one can obtain the average flux distribution for any day, month or year. This flux distribution obtained may then be applied on any solar cell to analyze the performance and obtain the current density distribution which may again be integrated to obtain any other electrical parameters of the solar cells. The flux distribution diagram can again be used to optimize the cell design and performance based on the metallic grid design, number of grid fingers, finger spacing, bus bar design and back contact of solar cell. Further, the thermal performance of the solar cell may be analyzed to obtain the temperature profile of the cell. Most of the LCPV applications do not need thermal management, and can work effectively with simple passive cooling arrangements. However, MCPV and HCPV applications require a special thermal management system involving a slightly complex design. While manufacturing the solar cells, they usually undergo testing under uniform illumination conditions. Using special masks as described in the earlier section based on the optical analysis of the concentrator, its performance can be analyzed well before it is placed in the real outdoor conditions and its electrical characteristics obtained. The optimization process involves mutual exchange of data between the different domains of required system, its optical performance, cell performance and thermal management. Based on several trails an optimum design could be attained for a particular application. It's equally important to keep an eye on the simplicity of manufacturing process and its associated costs, in order to attain the best CPV system for any given application. Chen and Yi [112] demonstrated the application of both ray tracing shown in Fig. 30 and simple slumping method which can be employed to manufacture a free form two-stage concentrator.

4. Measures to reduce the effect of non-uniformity

4.1. *Solar cell*

In order to translate the high performance of these concentrator cells into lower energy costs the CPV system must be designed with optimum operating characteristics. The concentrator cells need to have the right size and shape depending on the illuminated region in concentrating systems. Cells can take shapes of square, circle, rectangular and any other shape depending on the type of concentrating system. They also need to account for the variation in the flux intensity across their area. Cell doping can play an important role in the performance of solar cell, Weaver [113] studied the effects of design and process parameters on silicon concentrator cells performance especially the effect of doping. They compared three types of cells with n^+-p, back surface field (p^+n-n^+), and the p^+-n cells. They found

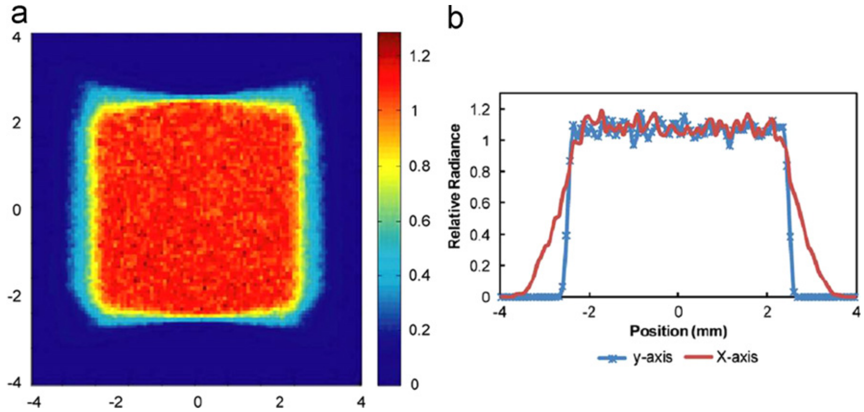

Fig. 30. Use of ray tracing to analyze the flux distribution in concentrator (a) flux distribution on the cell surface(b) flux distribution along the *x*–*y* axis [112].

that the p^+–n cells to be the most effective at higher concentrations. Khemthong and Iles [86] suggested that the cell size must be chosen to provide the required circuit current and voltage, within the limits set by the concentrator. Employing a suitable cell back surface ensures good heat transfer from the cell. The top-surface contact areas must be able to handle the planned peak current and the cell must also withstand a high voltage build-up. The conversion efficiency of a solar cell primarily depends on the product of three important factors they are the short circuit current density Jsc, the open circuit voltage V_{oc} and the curve fill factor FF. The LGBC cells can be optimized depending on the type of the concentrating system, by changing process parameters like the groove depth, finger pitch and copper thickness an improvement can be made in its overall performance for concentrator systems [46]. The improvement in the solar cell performance is dependent on several inherent factors [55,61] that affect the cell series resistance like the cell size, grid spacing, grid conductance, sheet resistance of the top and the bottom layer. Heasman et al. [55] developed the Czochralski Silicon (Cz–Si) solar cells for use up to $100\times$ concentrations. The cell design for lowest power loss and ease of production had two bus bars, 42 gridlines with a total grid line shading loss of about 9%. Optimized grid design has been seen as an important parameter in improving the solar cell efficiency [86]. A study by Mellor et al. [94] showed that optimization of the front contact pattern, by increasing the number of fingers to suit the degree of non-uniformity, can mitigate the decrease in each characteristic significantly. Some of the results showing the effects on fill factor and efficiency of the cell are highlighted in Fig. 31. Recently, Morvillo et al. [114] studied the influence of metal grid patterns on the performance of silicon solar cells at different illumination levels. Optimizing the grid structure minimizes the combined effect of emitter-layer resistance, grid-metal resistance, shading loss due to grid reflection, and contact resistance between the metal and the semiconductor. Cells based on new manufacturing techniques could prove to be capable of tolerating the non-uniform illumination. Special Sliver® cells [115] could also be used for combating the non-uniform illumination which occurs in concentrator systems.

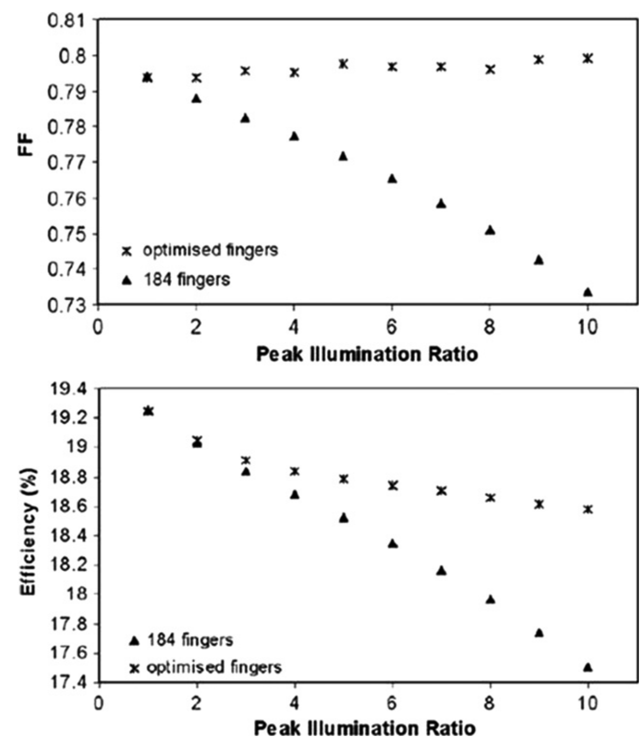

Fig. 31. Improvement in the Cell performance with optimization of fingers [94].

4.2. Concentrator element

A considerable improvement in the concentrator design and geometry can effectively reduce the effect of non-uniformity. A classical method employed to improve uniformity is to have a secondary optical element as shown in Fig. 32. [116] demonstrated the use of a Fresnel lens capable of reducing the effect of non-uniformity. A free form Koehler design [117] found the use of low-angle scattering reflectors to be effective in giving a uniform flux distribution, which results in a higher fill factor and improved the solar cell performance. Hatwaambo et al. [118] recently demonstrated the use of a semi-diffuse aluminum sheet reflector with rolling grooves oriented parallel to the plane of the solar cell

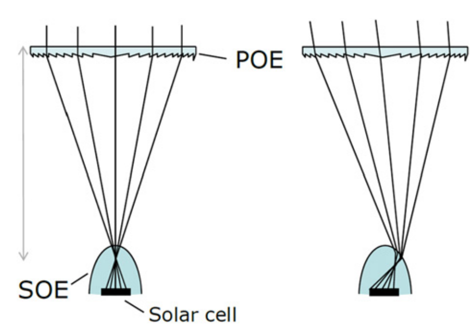

Fig. 32. Use of a Secondary Optical Element (SOE) can improve the uniformity [121].

module. The existence of these grooves helped in scattering the solar flux uniformly across the solar cell reducing the hot spot formation. The flux distribution across the solar cell could be very helpful in designing the concentrator design and manufacture. Methods of measuring the flux are presented by Adsten et al. [119]. Irradiation distribution diagrams were presented by Smyth et al. [120] as a function of the projection of the sun. These diagrams form a useful tool to visualize the annual or seasonal distribution on any CPV system whose acceptance angle primarily depends on the projected incident radiation. These could be helpful in determining potential facade's areas of building where CPC has the highest power output and cost effectiveness.

In the cases where there is uniformity of flux over concentrator cells [122], the degree of uniformity in incident flux becomes important while predicting the peak power at lab scale measurements. So it becomes important that the cells be measured under uniform illumination conditions which could be implemented by using occlusions. During their study on characterization of the spatial distribution of irradiance and spectrum in concentrating photovoltaic systems Victoria et al. [73] found that adding an SOE to a Fresnel lens significantly reduces those non-uniformities and improves performance of the system.

4.3. Tracking

An innovative way of tracking the sun known as [123] Tracking integrated concentrating photovoltaics was recently demonstrated. In this system tracking the complete CPV system or tilting the optical element of the concentrator is avoided and the absorbing surface is laterally moved along with the optical lens to track the sun. This could be a possibility which can be explored in future for reducing the external solar tracking therefore minimizing the impact of non-uniform illumination on the system.

4.4. Manufacturing

With improved manufacturing methods, the manufacture of the cell that can perform as predicted in its design can be achieved. New methods of improving the cell manufacture are always sought by the industry. A recent improvement developed at Narec is the incorporation of an Al BSF into the LGBC cell process. In addition, a concentrator cell to be operated at 2x requires lesser copper in its contact as compared to the cell to be operated at 100x. Optimization of copper thickness can be easily adjusted by varying the time in the copper plating bath. However this increases the time needed for batch manufacturing. The concentrators to be used in the CPV system should be accordingly manufactured with low errors and high tolerance. Conventional methods like continuous roll embossing, hot embossing, compression molding, glass molding are utilized for manufacturing the optical concentrators. Proper manufacturing can lead to excellent concentrators, without the chromatic aberration and high irradiance uniformity [116].

4.5. Thermal management

The non-uniformity of the incident solar radiation causes heating in the cell causing power loss and making it important to have a thermal management system coupled for its proper functioning. Both passive and active cooling may be applied to manage the thermal state of the solar cell. Use of air could be made to alleviate the temperature [24] in some low concentrating systems. Natarajan et al. [124] recently presented a study on the thermal management of the solar cells subjected to concentration of 10x. Using a passive cooling arrangement proved to be a viable solution for reducing solar cell temperature effectively. Several studies [125–128] have been performed using micro channels to provide cooling to electronic devices which could be very well applicable to CPV systems. Details of several other systems can be found under Royne et al. [83]. Recently, Chemisana and Rosell [93] modeled and experimentally evaluated the influence of the temperature profile generated via active cooling behind the CPV cell. In their study they evaluated the effects of having a Gaussian and anti Gaussian temperature profiles generated via cooling arrangements behind the cells as shown in Fig. 33. They found that, the Gaussian profile improved the electrical performance by

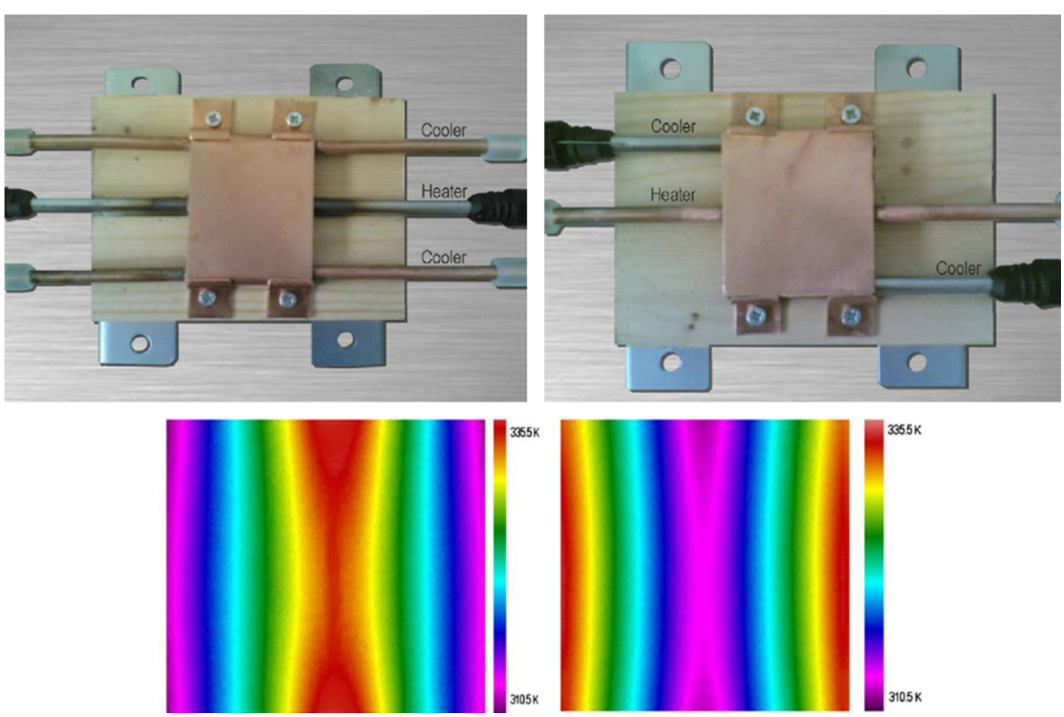

Fig. 33. Gaussian and Anti Gaussian profile generated via a thermal dissipater.

1.52%. On the other hand the anti Gaussian profile decreased the performance by 3%.

5. Conclusions

A review of the causes and effects of the non-uniform illumination on Concentrator solar cells has been presented. Major studies explaining methods used for modeling and experimental characterization are highlighted for both single junction and multijunction solar cells. The important parameters that could cause the non-uniformity include the concentrator geometry, design and manufacturing methods. The major effects of the non-uniformity are to decrease the electrical efficiency, cause non-uniform heating in the solar cell, decrease the fill factor ultimately increasing the $/watt produce. The non-uniformity is found to have impact on all types of concentrator system, however the impact is more pronounced in the case of HCPV systems.

Modeling of the effect of non-uniform illumination can be carried out using theoretical and finite element methods in 1-D, 2-D or 3-D. The profiles of the incident solar radiation after passing the concentrator can take any shape, however the most commonly studied profiles include the Gaussian profile. The experimental methods to study the impact of non-uniformity are still undergoing developments. Both single flash and multi-flash systems are adopted to measure the performance of concentrator solar cells. Use of lithographic masks could be made to produce the non-uniform illumination patterns to give performance results under the effect under these conditions. Outdoor testing methods for predicting the performance of the concentrator solar cells are also highlighted.

Optimization of the illumination profile on the concentrator solar cells requires proper concentrator design; however it is also possible to improve the solar cell design without compromising the solar concentrator efficiency. Forming grooves on the reflector surface helps in scattering the solar flux uniformly across the solar cell reducing the hot spot formation. Improvements in grid pattern and optical absorption properties on the front surface of the solar cell could prove to be useful in reducing the impact of non-uniform flux on the solar cells. It's important to maintain accuracy and tolerances while manufacturing the optical elements of the CPV system for better performance.

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